Feasibility study of Combined Cycle Gas Turbine (CCGT) power plant integration with Adiabatic Compressed Air Energy Storage (ACAES)

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Abstract: The paper presents the research outcome on integration of an Adiabatic Compressed Air Energy Storage system with a Combined Cycle Gas Turbine power plant to increase its operation flexibility. The study demonstrates the novel hybrid CCGT-ACAES plant including an extended operational load level range and increased operation flexibility which supports the power grid to allow more power generation from connected intermittent renewable energy sources. It is also shown that this new hybrid power plant will avoid the Combined Cycle plant gas turbine operating under the low load level. Lowering the minimum hybrid plant operational load level during air and Thermal Energy Storage charging process to the required minimum Heat Recovery Steam Generator load level eliminates the need for Combined Cycle Gas Turbine plant cycling operation increasing the lifetime of the plant components. Adiabatic Compressed Air Energy Storage plant concept is based on proved and well established direct two-tank Thermal Energy Storage technology used in Concentrated Solar Power plants. Improved hybrid plant flexibility is occupied by slight decrease (2%) in the plant efficiency. Further investigation into alternative advanced Thermal Energy Storage systems based on latent heat and chemical reaction heat would offer better hybrid plant round-trip efficiency across operational plant load level range.

Keywords: combined cycle gas turbine; compressed air energy storage; thermal energy storage; flexible operation; power plant.

1. Introduction

Efficient and flexible power plant operation is crucial in secure power system operation. Power plants play principal role in the grid frequency regulation process responding passively to the load changes and keeping the constant balance between load and generation. Majority of power plants have been designed to operate as base-load units with only limited load following or cycling capability. Increased share of renewable generation (mainly wind and solar) and its natural intermittency highly influence on conventional power plant operation regimes. Power generation units are expected to respond quicker to load changes (faster ramping up and down rates), work with lower load factors (less efficient) or they are forced to shifting operation regimes (overnight/weekend shutdowns). Current power system has emerged new operating requirements for conventional plants: frequency support, load-following operations, two-shift operations, island operations, black-start capability and very high start-up and operating reliability. All these factors impact on the plant components wear, highly increase the maintenance costs and negatively influence on the plant components lifetime.

Combined Cycle Gas Turbine (CCGT) plants are the most common natural gas fired option for base load and non-peak operation due to their wide capacity range and high efficiency (up to 60%) at full load [1]. CCGTs currently cover one third of the UK electricity production and 22% of global world electricity production [2]. Although Gas Turbine (GT) allows for very rapid unit response, the Steam Turbine (ST) is less tolerant to frequent and fast load changes, and the average CCGT rate of change of load is in the range of 4-9%/min in load-following mode [2]. The minimum CCGT load level for single-unit plant is limited to 40% (about 30% of GT load), therefore when the electricity price is low CCGT plants are forced to shut down (cycling operation). In recent years, plenty of research have been done to improve CCGT plants performance such as reduction of the minimum operational plant load level, decrease the start-up time of the system after cold shutdown in cycling operation, plant efficiency improvement and emission reduction in off-design conditions [3,4,5]. Similarly, majority of work have been focused on the damage of CCGT plant components caused by cycling operation and to assess their lifetime [6].

Hybrid and integrated energy storage application into conventional power plant process cycle seems to be great solution for more efficient power plant operation [7]. Also, several hybrid CCGT plant concepts have already been investigated. A review article introducing CCGT plant driven by a solar tower is an example of renewable energy source integration with Gas Turbine (GT) cycle [8]. The advantage of this system is reduced fuel consumption (natural gas) and consequently CO_2 emissions drop via preheating compressed air in the solar tower instead of burning fuel in GT's combustion chamber. Another concept relies on the solar power in an Integrated Solar Combined Cycle System (ISCCS) that uses solar power in bottoming steam cycle of CCGT which increases the plant efficiency up to 10% [9]. Liu *et al.* presented an interesting system that combines Compressed Air Energy Storage (CAES) with CCGT plant [10]. Proposed CAES-CC system has 10% better efficiency compared to conventional CAES plant. In this concept compressing intercooler heat can keep the steam turbine on hot standby effectively improving flexibility of the plant. Salvini presented another interesting system that combines CAES with CCGT plant [11]. In this case a part of flue gases from the outlet of GT is used to preheat the air in the expansion train of CAES plant in the storage discharging process. Proposed integration leads to fuel savings in CAES plant and consequently CO_2 emission reduction, although in this configuration the heat generated during air compression stage is wasted. Another step forward in CAES technology is to use the heat generated during air compression phase when the storage is charged and re-use it during expansion phase when the storage system is discharged. This concept called Adiabatic CAES (ACAES) system indicates high potential for large-scale energy storage systems with zero emission [12,13]. Another technical feasibility study has also been performed for CAES plants coupled with wind and solar energy [14].

Although some initial studies of CCGT-CAES plants have been already investigated, in this paper we propose a novel hybrid plant scheme with zero-emission ACAES plant integration. A hybrid CCGT-ACAES plant is investigated based on numerical modelling and simulations. The general concept is to take advantage of large-scale energy storage system and extract a part of compressed air from GT compressor outlet and feed it into ACAES plant in storage charging process during low load demand. When the load demand is high the air can be released and additional power can be generated during storage discharging process. In this article, a commercially available TES storage system is implemented based on established two-tank storage system used in Concentrated Solar Power (CSP) plants. To proof the concept, we developed mathematical models of CCGT, ACAES and novel hybrid CCGT-ACAES plants in EBSILON Professional software package. Next, the compressed air extraction experiment from GT compressor is simulated to assess the extracted air parameters and compared with air parameters at each compressor stage in ACAES model plant. Based on this comparison the optimal connection point for both models is selected. We optimized the hybrid CCGT-ACAES model parameters to ensure 8-hour charging and 2-hour discharging times which should be suitable for daily operation cycle. Finally, we performed the hybrid plant performance analysis in function of the plant load level. The results are discussed with suggestion for further round-trip power plant efficiency improvement.

2. Plant Modelling and Simulation

Mathematical modelling and simulations are considered as the first step towards the initial concept validation. It is difficult to implement any kind of air extraction experiment from running GT compressor. Furthermore, ACAES plant concept is at early stage, subsequently any real-scale plant has not been built yet. The hybrid plant concept investigated in this article requires both CCGT and ACAES detailed models implementation to accurately assess both plant performances in function of load level. Broad number of modelling tools can be found for power plant simulations study. From numerous software packages available on the market, such as: Aspen, APROS, Autodynamics, gProms, HYSYS, MATLAB/Simulink, MMS, SIMODIS, PowerSim and ProTRAX; the EBSILON®Professional (STEAG Energy Services GmbH, Germany) platform has been selected. This software package allows for comprehensive power plant process cycle implementation for steady-state and quasi-dynamic simulations and plant parameters optimization process. Although, physical equations describing all components in EBSILON®Professional software environment are valid for steady state calculation only it is possible to neglect the dynamic effects by performing series of simulations on a small timescale. It is realised by using a combination of 'Time Series' and 'ebsScript' feature at the programming level to create and simulate such quasi-dynamic systems. Furthermore, one of the biggest advantages of this software is possibility for TES system implementation, based on two-tank (hot and cold tank) storage system used in CSP plants. In this article, mathematical models of CCGT and ACAES power plants have been developed to simulate the plant process cycle and identify the model parameters. Comparison between air parameters in each model allows providing the optimal hybrid CCGT-ACAES plant configuration and further parameters selection.

2.1. CCGT Plant Model

Based on the available data a large-scale 294MW CCGT power plant model has been selected for implementation in the simulation software. The model consists of Heavy Duty SGT5-3000E(41Mac) gas turbine unit and the waste heat from GT is captured in triple pressure reheat Heat Recovery Steam Generator (HRSG) system. This configuration corresponds to current modern CCGT power generation unit. The plant model structure implemented in EBSILON®Professional software is illustrated in Fig 1. The main model parameters are listed in Table A1 (Appendix A).

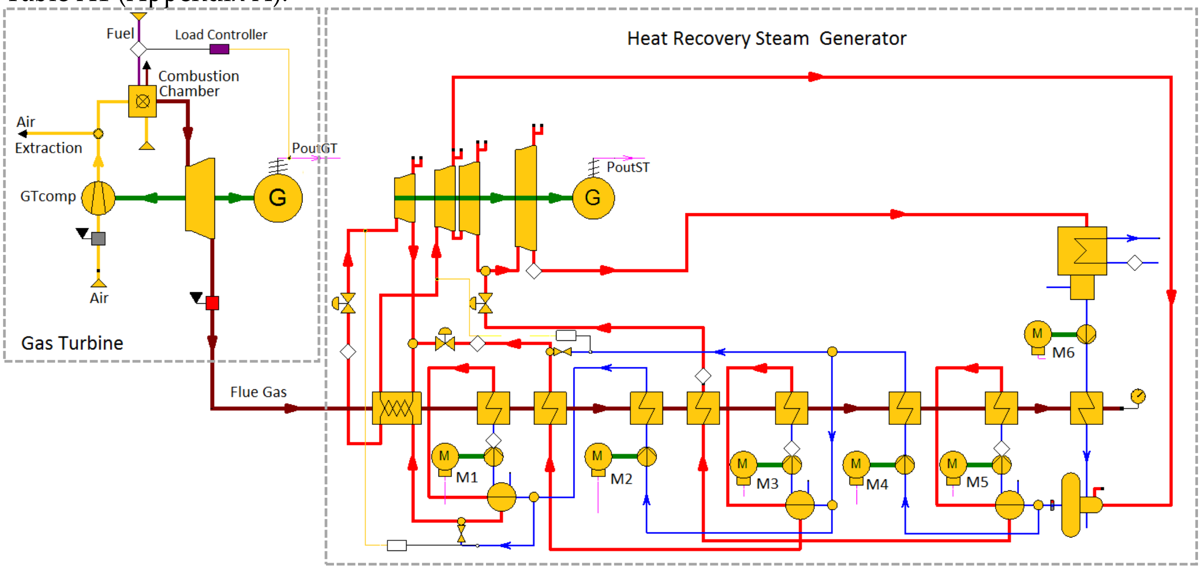


Figure 1. CCGT power plant process cycle.

Although the GT model can be represented in EBSILON by just one module from validated OEM gas turbine library with manufacturer specific performance data (developed in cooperation with VTU Energy GmbH), GT model is represented by separate components: compressor, combustion chamber, turbine/expander and synchronous generator. Therefore, in this configuration it is possible to simulate the air extraction process from GT compressor. CCGT load level is controlled by GT load level controller regulating the fuel mass flow to the GT combustion chamber within the range 30-100%. GT and CCGT unit efficiency can be calculated based on the following equations:

$$\eta_{GT}(\%) = 100 \times \frac{energy\ output}{energy\ input} = 100 \times \frac{P_{outGT}}{Q_{fuel}} \quad (1)$$

$$\eta_{CCGT}(\%) = 100 \times \frac{P_{outGT}+P_{outST}}{Q_{fuel}+Q_{ST}} \quad (2)$$

Where: P_{outGT} – Gas Turbine output power;
P_{outST} – Steam Turbine output power;
Q_{fuel} – heat input by the fuel;
Q_{ST} – feedwater pumps power consumption in steam cycle.

HRSG unit is a typical modern triple-pressure reheater system with the main steam parameters 120bar, 530°C and reheater steam parameters 30bar, 533°C. CCGT model plant provides high CCGT and GT unit efficiency (55.42% and 35.45%, respectively).

2.2. Adiabatic-CAES Plant Model

CAES plant is one of suitable options for large-scale energy storage facility with the power output at similar level to a pumped hydro storage plant. This is also proven and mature technology as Diabatic-CAES plants are already operating in Huntorf, Germany (1978) [15] and McIntosh, United States (1991) [16]; the third one Larne project in Northern Ireland is on planning permission stage [17]. Although that DCAES plant efficiency is quite high (42% and 54%, respectively for the existing plants), these plants need external heat source to preheat the air during storage discharging phase. Adiabatic-CAES plant is another step forward, as the heat for air expansion process in discharging stage comes from Thermal Energy Storage which is charged during air compression in the plant charging stage. Both air and TES storage systems should be designed to operate in parallel and the capacity of both storage vessels should be sufficient for full ACAES cycle (charge, storage and discharge phase). Although there are no existing ACAES plants, two projects are in a planning stage: ADELE project in Germany [18] and ALACAES project in Switzerland [19]. Both projects require the air storage at the operating pressure in the range of 70-100bar. TES storage concept is a pressurized container packed with bed of stones and ceramic bricks that operates in high temperatures 600-800°C. The round-trip efficiency is estimated to be around 70-72%.

In our work, ACAES plant model implemented in EBSILON®Professional is based on existing DCAES plants parameters and available information related to the future ACAES projects. The following assumptions have been made:

- The plant operation regime is 8-hour charging, 14-hour storage and 2-hour discharging times.
- Air storage in salt cavern with the storage pressure 70-100bar and temperature 50°C.
- Constant compression power of 60MW in charging mode and expansion power of 135MW in discharging mode.
- Compression train consist of four stages (two LP and two HP compressors) with two intercoolers cooling down the air to 120°C and one aftercooler cooling the air to the storage temperature of 50°C.
- TES system has been adopted from commercially available technology used in CSP plants. Two-tank direct storage system with synthetic thermal oil has been used as a Heat Transfer Fluid (HTF). Therminol VP1 has been selected with operation temperature 40°C in cold tank and 300°C in hot tank.
- Expansion train works in sliding pressure mode (98-68 bar for 1st stage and 9.9-8.25bar in 2nd stage. Two heat exchangers preheating the expanding air to 290°C.

ACAES power plant model structure implemented in EBSILON®Professional software is illustrated in Fig 2 and the main plant parameters are listed in Table A2 (Appendix A).

ACAES plant efficiency is calculated based on the following equation:

$$\eta_{ACAES}(\%) = 100 \times \frac{P_{outAIR} \cdot t_{disch}}{Q_{COMP} \cdot t_{charg} + Q_{EXP} \cdot t_{disch}} \quad (3)$$

Where: t_{disch} – storage discharging time [s],
t_{charg} – storage charging time [s],
P_{outAIR} – ACAES output power [MW],
Q_{COMP} – total power consumed in ACAES charging mode by the compressor train and TES pumps (Mc1-Mc3) [MW],

Q_{EXP} – total power consumed in ACAES discharging mode by TES pumps (Md1, Md2) [MW].

Simulated ACAES plant model round trip efficiency (η_{ACAES}= 56.78%) is lower than the claimed efficiency of future ACAES projects (70-72%) [20], which were calculated using ideal assumptions.

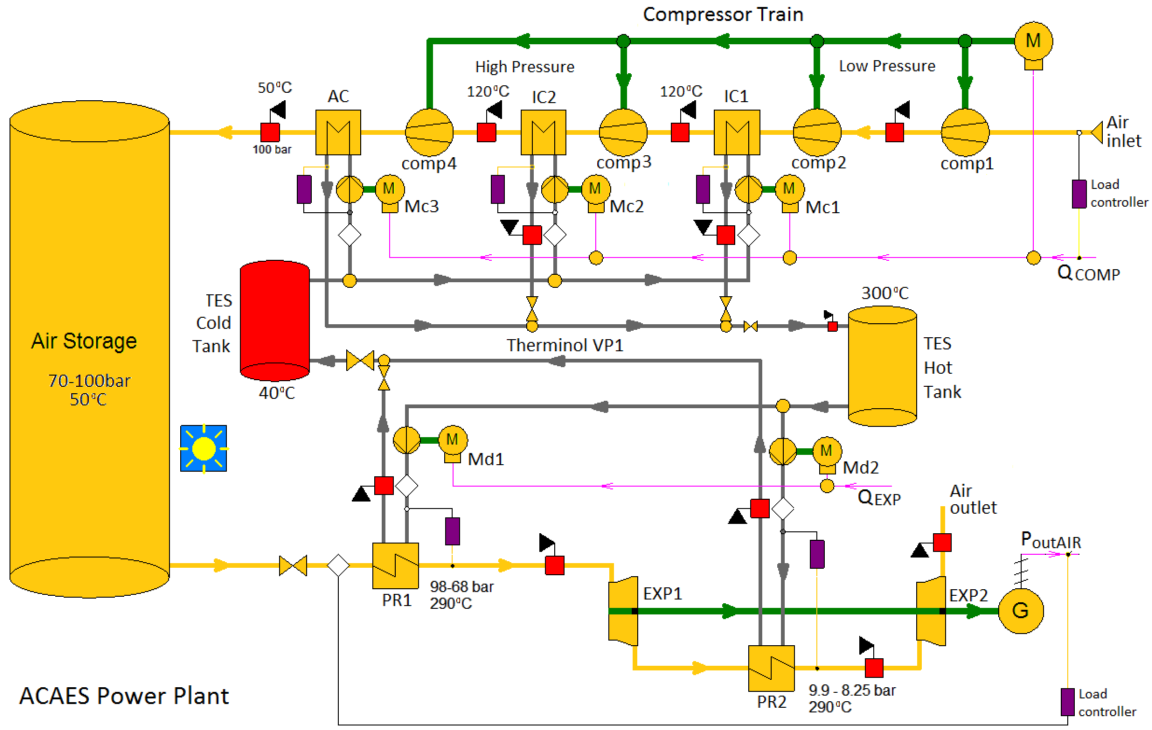


Figure 2. ACAES power plant process cycle. Where: comp1-comp4 – compressor stages; IC1, IC2 – intercoolers; AC – aftercooler; Mc1-Mc3 – HTF pumps in charging mode; Q_{COMP} – total power consumed in charging mode; PR1, PR2 – air preheaters; EXP1, EXP2 – air expanders; Md1, Md2 – HTF pumps in discharging mode; Q_{EXP} - total power consumed in discharging mode.

The volume of a storage tank can be calculated based on the air parameters in the storage cavern according to the following equation:

$$V_{AIR}(m^3)=\frac{\dot{m}_{AIR}\cdot t_{charg}}{\rho_{AIR|100bar}-\rho_{AIR|70bar}} \tag{4}$$

Where: $\dot{m}_{AIR}$ – air mass flow to the storage cavern [kg/s],
$\rho_{AIR|100bar}$ – density of air at 100bar in the storage tank [kg/m^3],
$\rho_{AIR|70bar}$ – density of air at 70bar in the storage tank [kg/m^3].

The required volume of air in the salt cavern (63893.12m^3) corresponds to the storage volume required by existing DCAES McIntosh plant for 8-hour charging time (about 66176m^3) and it is two times smaller than Huntorf plant (150000m^3). TES system tanks are assumed to be over-ground storage vessels operating at 6bar pressure to avoid two-phase Therminol VP1 operation. The maximum level of the tank is estimated at 12582.51t, which is two times smaller than Andasol 1 CSP plant TES tank filled with 28500t molten salt (60%$NaNO_3$+40%KNO_3) [21].

2.3. CCGT-ACAES Plant Concept

A general concept of CCGT-ACAES plant is illustrated in Fig 3. The CCGT plant is the core of the system and can be operated standalone following the load demand request from the grid. ACAES plant is activated when the load demand is low and we would like to get the advantage of using the energy storage system. In the air storage charging phase, a part of compressed air from GT compressor is feed into the ACAES plant. GT compressor is acting as the first stage of ACAES compressor train and remaining ACAES compressors are also driven by GT shaft. Consequently, entire mechanical power generated by GT is consumed by air compressor train and the power output from GT synchronous generator is reduced to zero. At the same time flue gases flow from GT outlet should be able to keep HRSG unit operating at the lowest load level. 8-hour storage charging time should eliminate HRSG overnight shutdowns. Simultaneously to the air storage system, the heat generated during air compression process in charging mode is captured and stored in TES system. Storage discharging process can be activated at any time, as it is independent from CCGT process. Compressed air is preheated using the heat from TES system and expanded in two stage expanders. Additional power boost is available for 2 hours. ACAES integration into CCGT plant should provide the following advantages:

- more flexible power plant operation,
- lowering the minimum plant load level during storage charging process,
- power boost during storage discharging process,
- reduced CO_2 emission,
- less frequent plant shutdowns and faster ramping,
- reduced HRSG thermal stresses and increased lifetime of plant components.

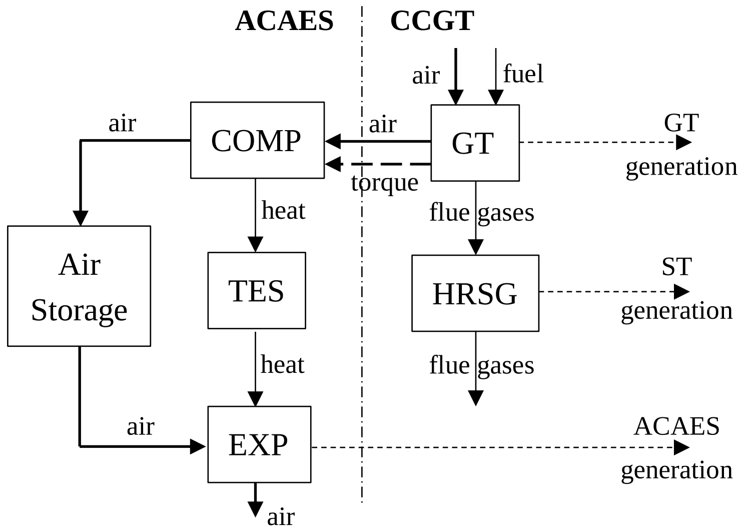


Figure 3. CCGT-ACAES power plant process flowchart.

To assess the technical feasibility of the concept it is necessary to match the air parameters from the GT compressor extraction point to the required air parameters by ACAES plant. CCGT-ACAES plant model structure is based on the simulation results for CCGT and ACAES models performance (presented in the next sections 3.1 and 3.3) and it is described in detailed in Section 3.3.

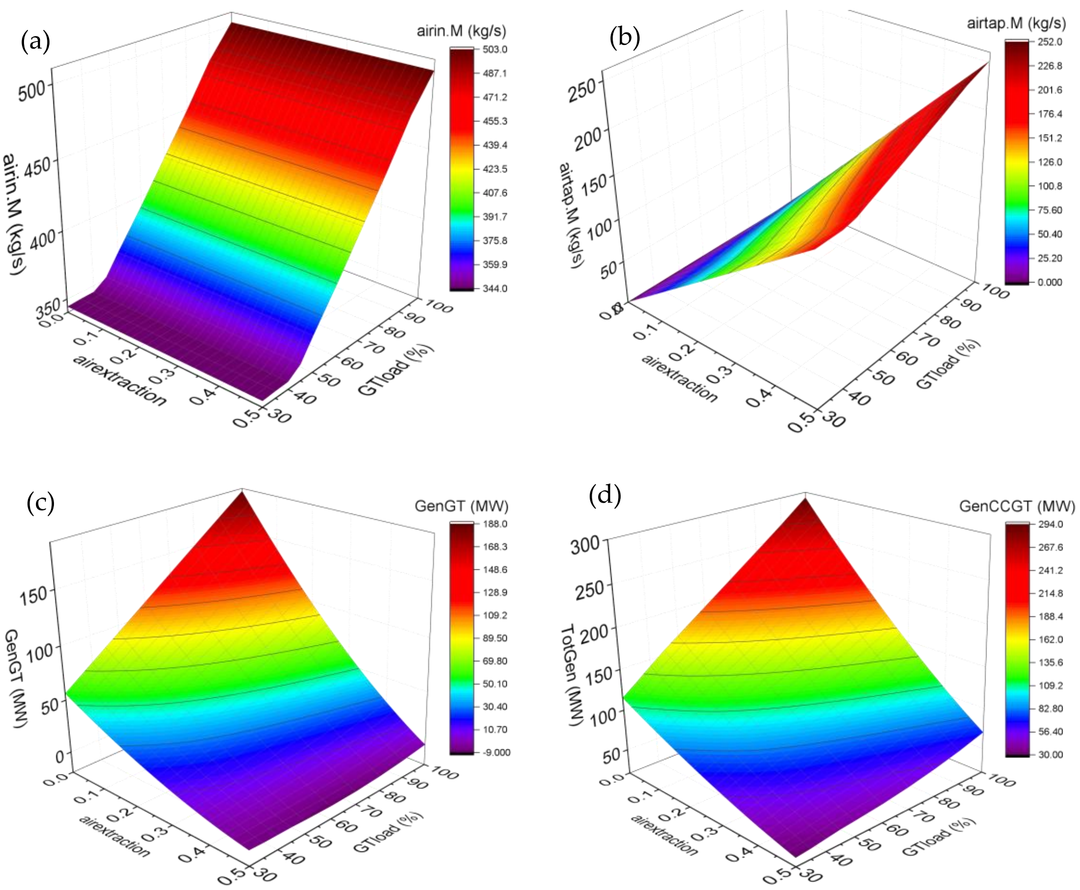
3. Simulations

CCGT-ACAES plant concept implementation requires a comparison between both plants performance in function of load level and extracted air mass flow. The objective is to match the parameters of the air (mass flow rate, pressure and temperature) extracted from GT compressor outlet to the parameters of air required by ACAES plant in the storage charging process. Two simulations have been performed to assess the air parameters. The first one simulates the air extraction from GT compressor model in function of GT load. Then the ACAES plant model performance is simulated in the storage charging processes for different storage pressure levels from empty to fully charged storage. The comparison should assess the potential to use GT compressor as a part of ACAES compression train. Finally, the complete CCGT-ACAES plant model simulation is performed, as the air extraction experiment does not take into consideration ACAES compressors load to the GT. Finally, all hybrid CCGT-ACAES plant model parameters are optimized to achieve 8-hour storage charging and 2-hour discharging time.

3.1. GT air extraction experiment

Air extraction experiment from GT compressor outlet has been performed in function of GT load level in the range 30-100%. The rate of extracted air is a percentage of the total air mass flow at the inlet to the GT and has been simulated in the range 0-50%. The results in a form of colour map surface area are depicted in Fig 4 with air extraction on the x-axis, GT load level (in %) on y-axis and simulated specific variable on the z-axis.

Air extraction from GT compressor outlet has significant influence on the CCGT plant performance. Inlet air mass flow to GT (airin.M) is a function of GT load level only and it is maintained constant for specific GT load level (Fig 4a). Extracted air mass flow from GT compressor (airtap.M), as a percentage of the GT inlet air mass flow, is depicted in Fig 4b. Power output from CCGT unit (Fig 4d) decreases with decreasing GT load level and supplementary air extraction from GT compressor additionally decreases generated power. For air extraction at 50% level all mechanical energy from GT is consumed by the GT compressor (Fig 4c). CCGT plant has the highest efficiency for the design condition (η_{CCGT}=56.46%; η_{GT}=36.08%) and decrease in GT load level. Additional air extraction from GT compressor causes further efficiency drop (Fig 4e and Fig 4f). The parameters of extracted air also change in function of GT load level and air mass flow. The highest parameters are reached for the design condition (16 bar, 410°C). Temperature and pressure of extracted air decreases with decreasing GT load level and increasing extracted air mass flow (Fig 4g and Fig 4h). GT outlet flue gases mass flow (GTout.M) and temperature (GTout.T) are also affected by the air extraction from GT compressor. Lower inlet air mass flow to GT combustion chamber causes increase the GT flue gas outlet temperature and decrease mass flow (Fig 4i and Fig 4j). HRSG performance is significantly affected at low GT load level and high air extraction from GT compressor. To fully assess the potential of air extraction from GT it is necessary to compare the extracted air parameters (mass flow, temperature and pressure) with the air parameters at each stage of ACAES compressor train, and this has been performed and is presented in the next section.



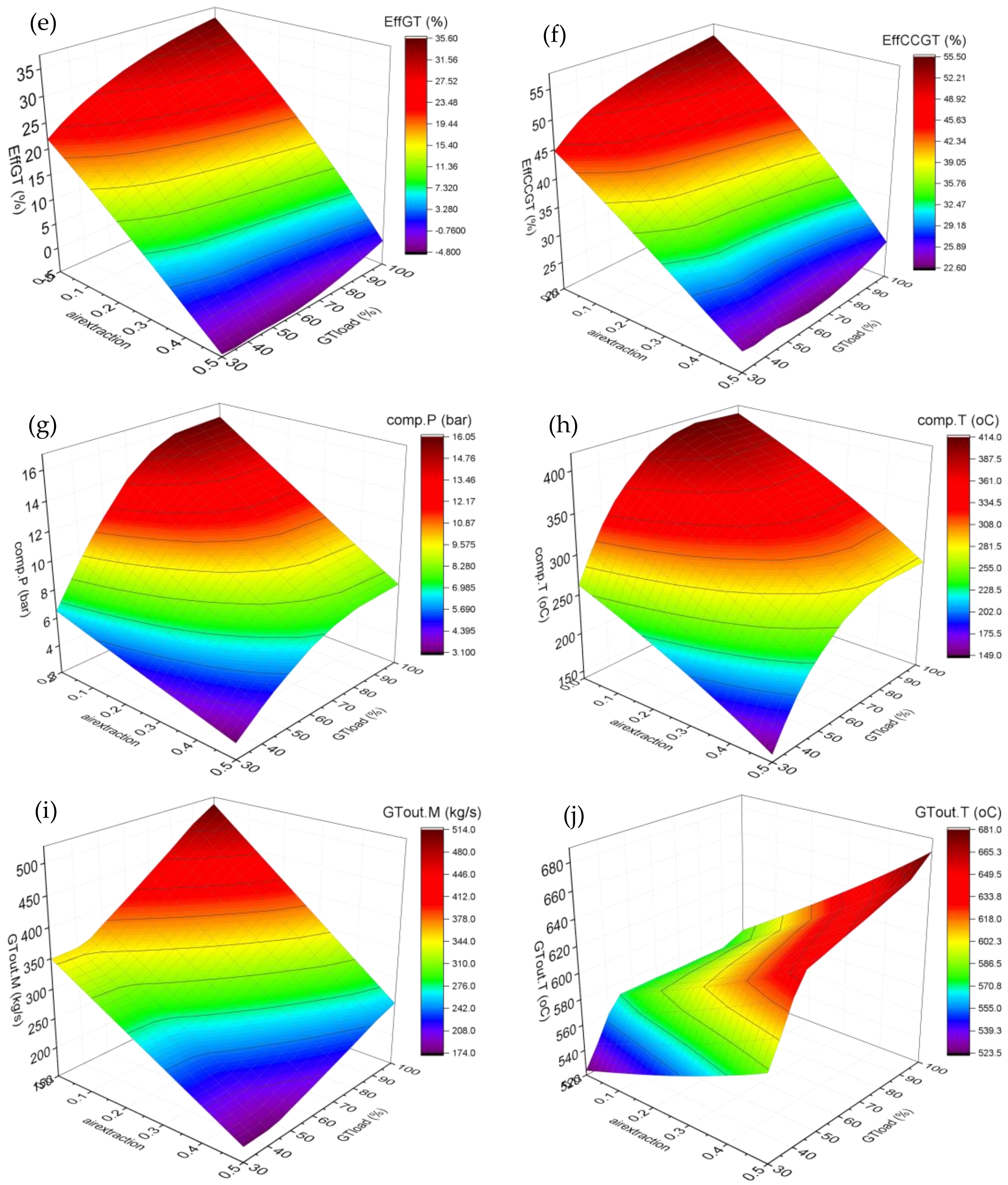


Figure 4. CCGT air extraction experiment results.

3.2. ACAES operation performance

The second step to assess the technical feasibility of the CCGT-ACAES hybrid plant concept is to validate ACAES plant model performance. To assess which part of ACAES compression train can be substituted by GT compressor, it is necessary to assess the air parameters at each ACAES compressor stage. Air mass flow, temperature and pressure change during the air storage charging process, as the storage pressure increases from the minimum to the maximum level. ACAES plant model performance has been simulated for air storage charging process in function of the air pressure in the range 70-100bar. As the air storage charging process is a slow process (8 hours from empty to fully charge) a steady-state analysis can be performed to assess the air parameters with acceptable accuracy. The results are depicted in Fig 5.

It is considered to maintain constant charging power of 60MW during ACAES charging process. Air pressure in the storage cavern increases from minimum level 70bar to the maximum 100bar. Consequently, the air pressure at each compression stage also increases accordingly (Fig 5a).

The first compressor (comp1) increases the air temperature to 140°C which is too low value to capture the heat by HTF (Fig 5b). Another compressor stages (comp2, comp 3 and comp4) increase the air temperature above 300°C which is sufficiently high for the heat extraction process with Therminol VP1. Two intercoolers are installed behind these compressors (comp2 and comp3) and cool down the air to 120°C. An aftercooler is installed at the outlet of the compressor train (comp4) and cool down the air to the storage cavern temperature of 50°C. Air pressure ratio for each compression stage is around 3 and increases slightly with the charging process (Fig 5c). During the air storage charging process, the air mass flow decreases from 78.7 to 71.7 kg/s (Fig 5d). Corresponding HTF mass flow from cold to hot TES tank also decreases accordingly and as the result, the temperature of HTF increases during ACAES charging process from 285°C to 305°C (Fig 5e).

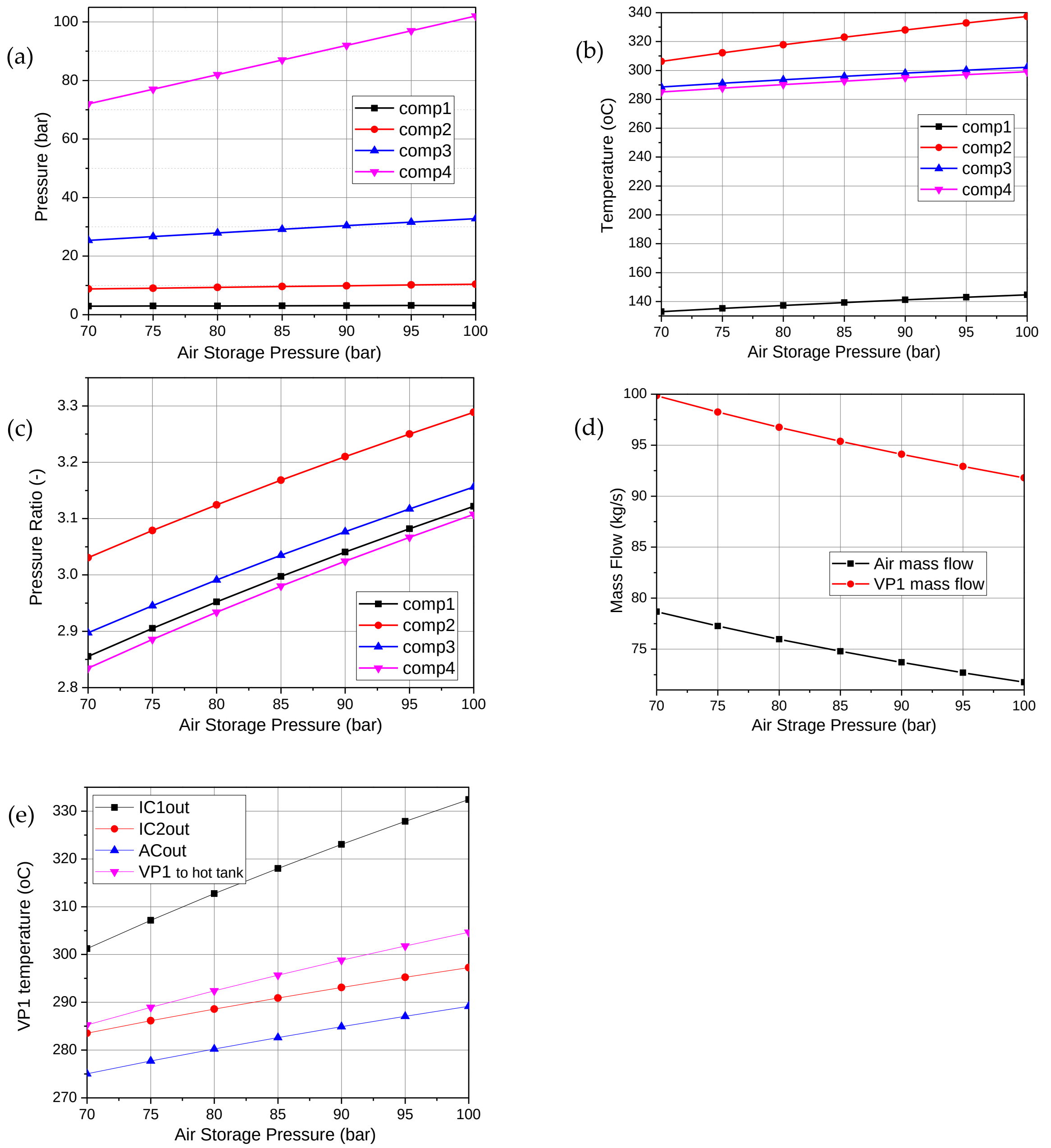


Figure 5. ACAES operation in storage charging mode.

To substitute ACAES compressor stages it is necessary to get the same or higher air parameters at the air extraction point from GT compressor. Assuming the same air mass flow as it is required by

ACAES plant in charging mode (the range of 70-80kg/s), the comparison between air pressure and temperature for both models are presented in Table 1 and Fig 6.

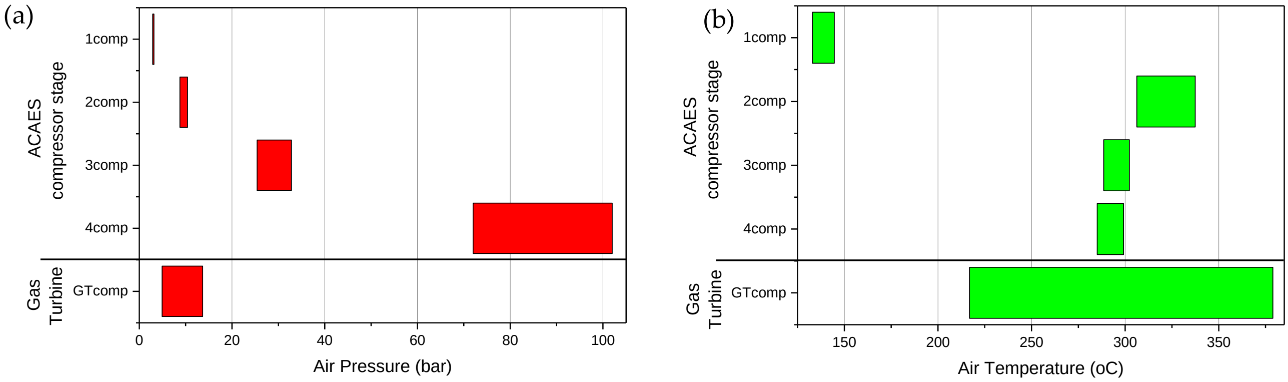


Figure 6. The results of comparison between (a) pressure and (b) temperature at the outlet of ACAES compressors stages and GT compressor for air mass flow 70-80 kg/s.

According to the obtained results, the air pressure from GT compressor entirely covers the air parameters at the outlet from 2nd ACAES compressor (Fig 6a). Furthermore, the temperature of air from GT compressor also covers the required air temperature from 2nd CAES compressor (306-338°C) (Fig 6b). This initial assessment allows assuming that GT compressor may successfully substitute ACAES low pressure compression train (comp1 and comp2 in Fig 2).

Table 1. ACAES and CCGT compressor outlet air parameters.

Model	Compression stage	Pressure		Temperature	
		min	max	min	max
		bar	bar	°C	°C
ACAES	1st Compressor	2.89	3.16	132.96	144.63
	2nd Compressor	8.76	10.40	306.23	337.44
	3rd Compressor	25.40	32.82	288.55	302.24
	4th Compressor	72.00	102.00	285.05	299.16
CCGT	GT Compressor air tap	4.92	13.67	216.84	378.89

According to the initial concept GT also drives remaining ACAES compressors (comp3 and comp4), therefore it is necessary to implement and simulate CCGT-ACAES plant model to fully assess this hybrid plant concept.

3.3. CCGT-ACAES Model

CCGT-ACAES plant model structure implemented in EBSILON®Professional is based on the results received from CCGT and ACAES plant model performance simulations and it is illustrated in Fig 7. During 24-hour operation the plant should be able to work in three different modes:

1. **CCGT-ACAES charging mode –** in this mode GT compressor is acting as the first stage of ACAES compressor train (substituting comp1 and comp2). The remaining compressors (comp3 and comp4) are driven by GT shaft. All mechanical power is consumed by compressors and the power output from GT generator is zero (P_{outGT}=0). The outlet flue gas flow from GT keeps HRSG unit running at minimum level and generating power (P_{outST}). This mode is available for 8 hours from discharged to fully charged storage.
2. **CCGT-ACAES storage mode –** in this mode the storage is maintained at constant level (empty, partly charged or fully charged) and the plant can operate as ordinary CCGT plant (P_{outGT} and P_{outST} is generated). This mode should be available for 14 hours.

3. **CCGT-ACAES discharging mode** – as the storage discharging part (air preheaters PR1 PR2, expanders EXP1 and EXP2) is able to operate independently from CCGT and additional power is generated by the air expanded from the storage (P_{outAIR}). Power boost is available for 2 hours.

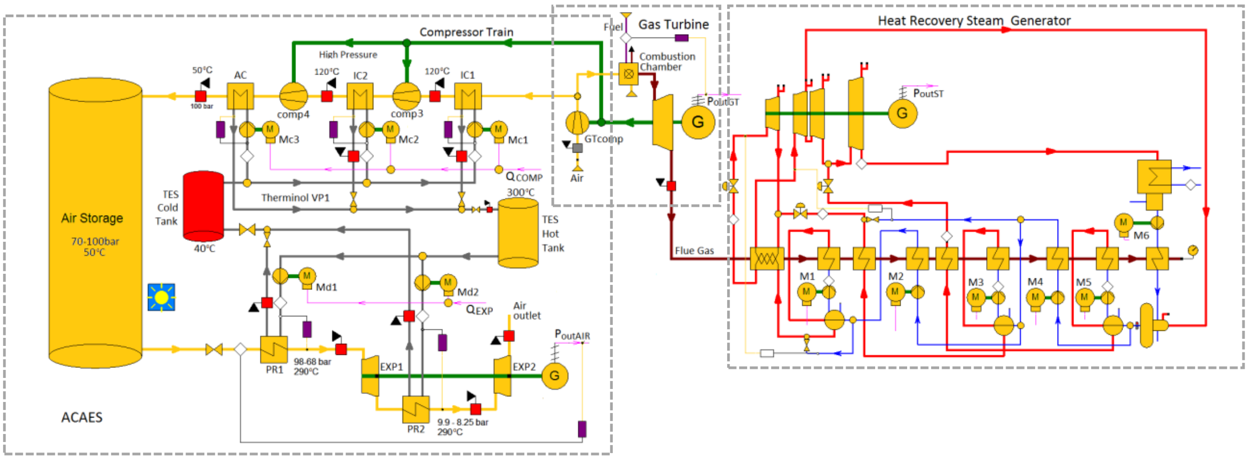


Figure 7. Hybrid CCGT-ACAES power plant model implementation in EBSILON®Professional.

Two types of CCGT-ACAES plant efficiencies can be calculated. The first one is the total CCGT-ACAES plant efficiency in ACAES mode ($\eta_{total(ACAES)}$) which is calculated according to Equation 5. In this mode CCGT part of the plant model is used only for storage charging process (8 hours) whereas it is shut down during discharging processes (2 hours). Based on this definition it would be possible to compare this efficiency with ACAES round-trip plant efficiency.

$$\eta_{total(ACAES)}(\%) = 100 \times \frac{P_{outST} \cdot t_{charg} + P_{outAIR} \cdot t_{disch}}{(Q_{fuel} + Q_{ST} + Q_{VPcharg}) \cdot t_{charg} + Q_{VPdisch} \cdot t_{disch}} \quad (5)$$

Where: t_{charg} – storage charging time [h];
t_{disch} – storage discharging time [h];
P_{outAIR} – output power from ACAES part [MW];
P_{outST} – output power ST cycle [MW];
Q_{fuel} – heat input by the fuel [MW];
Q_{ST} – power consumption for feedwater pumps in steam cycle [MW];
$Q_{VPcharg}$ – power consumption for TES pumps in charging mode [MW];
$Q_{VPdisch}$ – power consumption for TES pumps in discharging mode [MW].

The second CCGT-ACAES plant efficiency considers all three plant operation modes described at the begging of this section. Taking into account also the time when the concept hybrid plant opareates as standard CCGT plant, the total efficiency is calculated based on the following equation:

$$\eta_{total}(\%) = 100 \times \frac{(P_{outGT} + P_{outST}) \cdot t_{charg} + (P_{outGT} + P_{outST} + P_{outAIR}) \cdot t_{disch} + (P_{outGT} + P_{outST}) \cdot t_{storage}}{(Q_{fuel} + Q_{ST} + Q_{VPcharg}) \cdot t_{charg} + (Q_{fuel} + Q_{ST} + Q_{VPdisch}) \cdot t_{disch} + (Q_{fuel} + Q_{ST}) \cdot t_{storage}} \quad (6)$$

Where: P_{outGT} – output power from GT cycle [MW],
$t_{storage}$ – CCGT-ACAES storage mode operation time [h].

In Equation 6 it is necessary to provide values for generated and consumed power (P_{outGT}, P_{outST}, P_{outAIR}, Q_{fuel}, Q_{ST}) during charging, storage and discharging phase (t_{charg}, $t_{storage}$, t_{disch}). The CCGT-ACAES plant model performance results are presented in the next section.

3.4. CCGT-ACAES operation performance

Although majority of model parameters from CCGT and ACAES models are taken to the hybrid CCGT-ACAES model configuration, the parameters optimization should be carefully performed to fulfil the following assumptions:

- in the storage charging phase all mechanical power from GT is consumed by the compressor train (GTcomp, comp3 and comp4). Consequently, the power generation from GT generator equal to zero (P_{outGT} = 0). HRSG unit is also able to operate at the lowest load level (P_{outST} > 0).
- Compressor train should be able to fully charge the air storage from 70bar (empty storage) to 100bar (fully charged) in 8 hours.
- Simultaneously, HTF (Therminol VP1) should be preheated from 40°C (TES cold tank storage temperature) to 300°C (TES hot tank storage temperature).
- The volume of storage system (both air and TES) should be capable for 2-hour power generation (P_{outAIR} > 0).

The optimal CCGT-ACAES plant model parameters have been tuned in storage charging mode in function of the GT load level within the range 30-100%. Furthermore, the optimal hybrid plant parameters have been determined for the maximum pressure level in the air storage tank (100bar). The results (in points every 5 or 10%) are depicted in Fig 8.

Air mass flow rate to the storage cavern is a linear function of GT load level (Fig 8a). Corresponding HTF mass flow is also proportional to GT load level. Similar to the results received for the GT air extraction experiment performed in Section 3.1, the air parameters from GT compressor outlet are the highest for the higher GT load levels with the peak values around 80% (Fig 8b). Consequently, the pressure ratio across ACAES compression train (Fig 8c) decreases for GT compressor whereas it increases for comp3 and comp4 with decreasing the GT load level. For the lowest GT load levels, the pressure ratios of each compressor are at the similar level (around 5). Corresponding maximum air pressure at the outlet from each compressor stage is depicted in Fig 8d. Air temperature leaving each compressor (Fig 8e) decreases for GT compressor whereas increases for comp3 and comp4 with decreasing the designed GT load. Heat transferred via intercoolers and aftercooler preheat the HTF from 290°C to the maximum of 300°C for GT load level around 40%. Air and TES storage volumes, which according to the assumption should be charged within 8 hours, are proportional to the air and HTF mass flow entering the storage vessels. Higher storage volume for higher GT load significantly increases the total cost of the storage. Consequently, the lowest cost of storage can be found for the lowest designed GT load levels (Fig 8f). Power output from hybrid CCGT-ACAES plant model during storage charging (P_{outST}) and discharging (P_{outAIR}) processes is illustrated in Fig 8g. Both values are proportional to the GT load level. The maximum value of generated power during discharging phase (within 2 hours) is almost triple between the lowest and the highest GT load level. The last Fig 8h illustrates the total plant efficiencies calculated according to Equation 5 and Equation 6 in Section 3.3. Comparing hybrid plant model efficiency in ACAES mode (GT operates only during storage charging process), the maximum efficiency for the highest designed GT load level ($\eta_{total(ACAES)}$=46.82%) is 10% lower than for ACAES plant model simulated in Section 3.2 (η_{ACAES}=56.78%). This efficiency decreases with decreasing GT load level to the lowest value of 43.93%. The total CCGT-ACAES unit efficiency with considering the CCGT part of the plant running at full load also during storage process (14 hours) is nearly constant at the average level η_{total}=52.5% across the entire designed GT load level. The peak value η_{total}=52.66% is reached for GT load level around 45%.

Based on the received results the optimal CCGT-ACAES plant model parameters determined in storage charging phase are for 40% GT load level. For this condition, the air parameters extracted from GT compressor are high enough to successfully substitute LP compressor train in ACAES plant model. Also, TES temperature entering the hot tank reaches the highest level of 300°C. Another important factor is that during storage charging process HRSG unit can be still operating at its minimum load. The comparison between different CCGT-ACAES plant operation modes are illustrated in Fig 9a (in MW) and Fig 9b (in %). As a reference point the rated CCGT plant load level is considered (293.45MW).

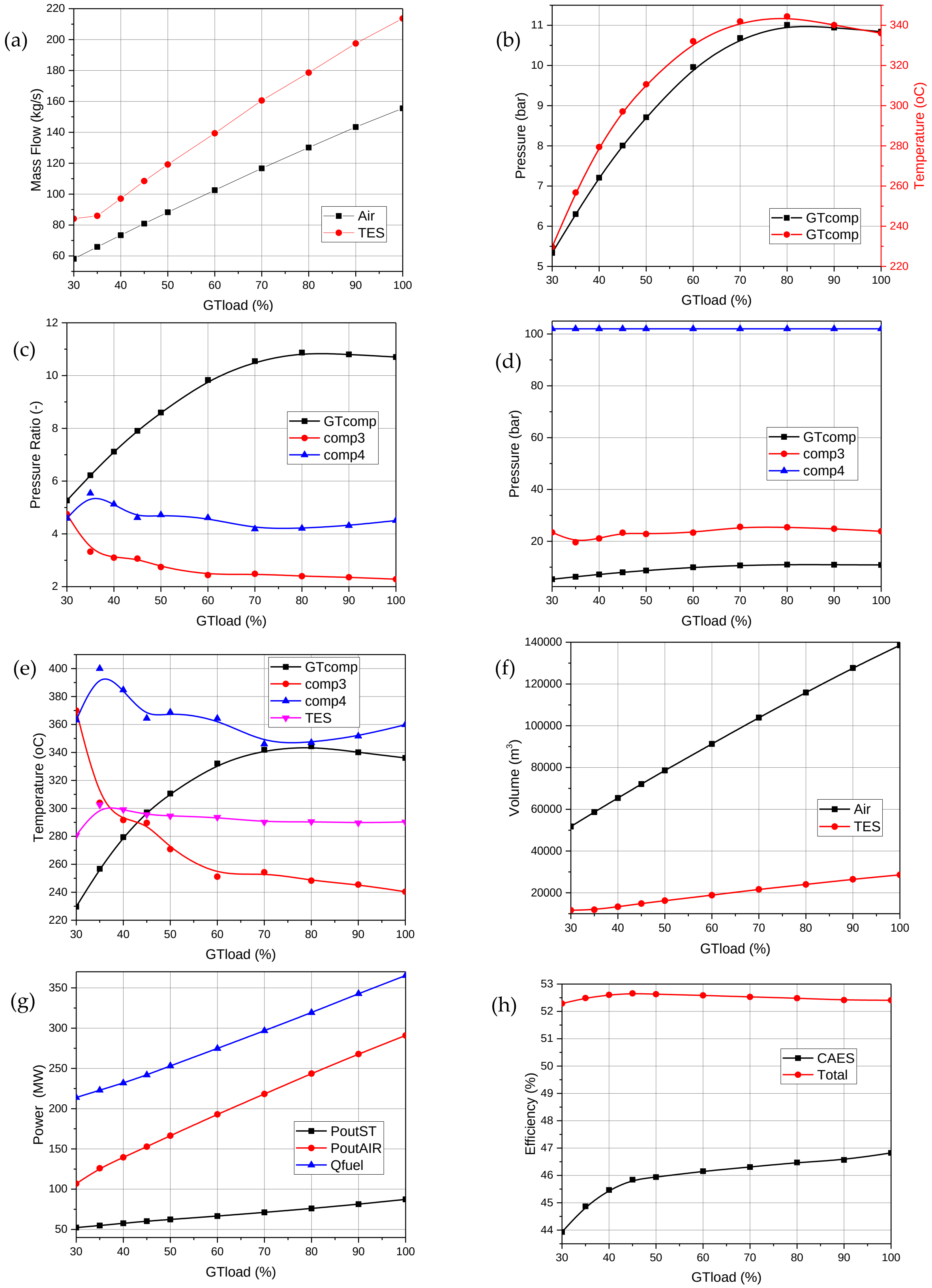


Figure 8. CCGT-ACAES plant model parameters in storage charging mode.

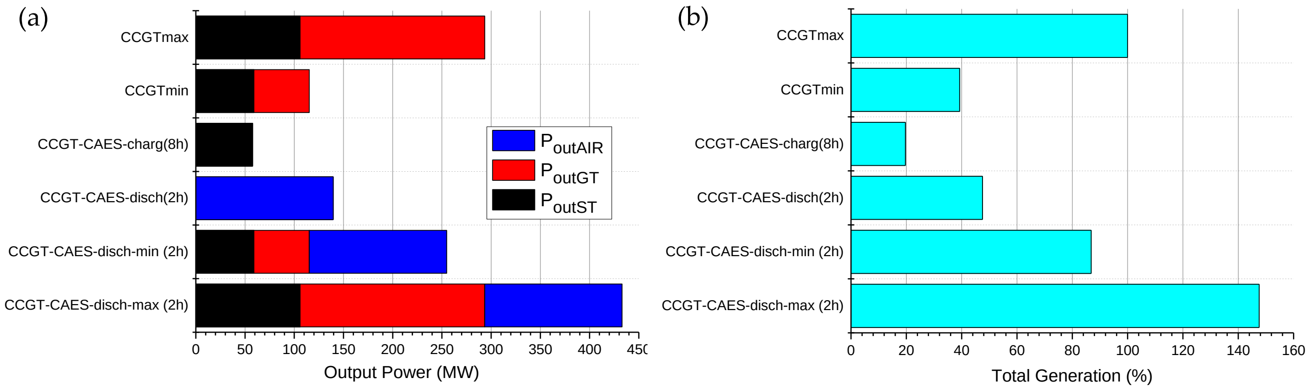


Figure 9. CCGT-ACAES vs CCGT power output for all considering operating modes (a) in MW, (b) in %.

The first two stack bars represent CCGT plant model operational level which is in the range of 39-100% (115.27-293.45MW). Hybrid CCGT-ACAES plant in the storage charging mode is able to reduce the plant load level to 19.66% (57.68MW) for 8 hours from discharged to fully charged storage. GT is used to drive entire compressor train and the outlet flue gas from GT is running HRSG unit at the lowest load level. During the plant discharging time (2 hours) the power generated from ACAES part is able to deliver 47.55% power boost (139.54MW). The hybrid plant can increase the power output to 147.55% (432.99MW).

Power generated by CCGT-ACAES plant in function of GT load level is presented in Fig 10a for all possible plant operation modes described at the beginning of Section 3.3: charging, discharging and storage modes. It is also necessary to compare the efficiency of the hybrid CCGT-ACAES plant with the efficiency of standalone CCGT and ACAES plants. The results in function of GT load are depicted in Fig 10b. Hybrid CCGT-ACAES plant efficiency in ACAES mode (the black line) calculated according to Equation 5 is much lower than the ACAES efficiency, which is estimated at the 56% level. Total efficiency of hybrid CCGT-ACAES plant (the red line) calculated according to Equation 6 is only 2% lower than CCGT plant model efficiency (the blue line). Increased operational flexibility of the hybrid plant has minor impact on the total unit efficiency.

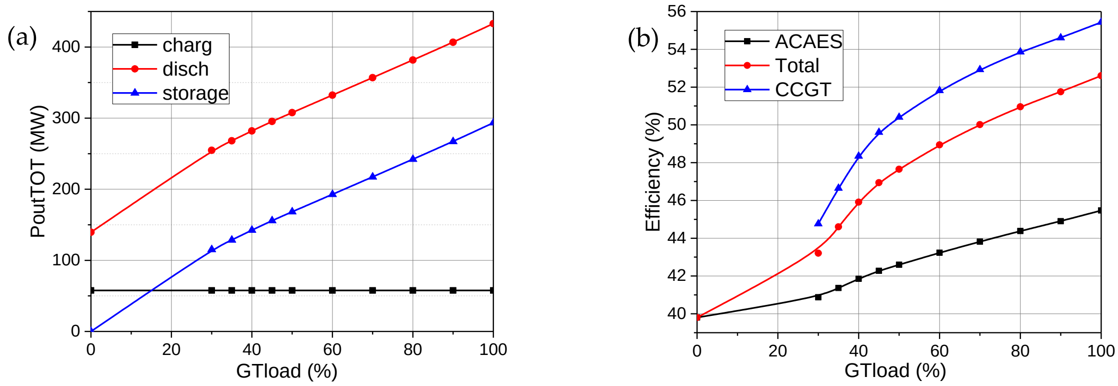


Figure 10. CCGT-ACAES plant model total power generation and efficiency comparison.

This specific example has been chosen to allow 2-hour storage discharging time covering the peak demand in the grid. ACAES discharging process allows for 135MW power generation which results in 47.5% power boost above the rated 293MW power delivered from CCGT part of the plant. A sensitivity analysis has also been performed to fully assess the potential of this hybrid plant. Relation between storage discharging time in function of storage charging time and discharging power level (only from ACAES part of the hybrid plant) is illustrated in Fig 11. We can find nearly linear relation between storage charging and discharging times for the same discharging power level. It is necessary to assure identical charging and discharging times for both: air storage and TES storage simultaneously. We can also observe an exponential relation between discharging power and discharging time. Lower ACAES discharging power allows for much longer discharging time.

In practise it is necessary to provide an adequate power level allowing to cover peak demand in the power system. The size of the storage system should also be carefully selected to particular case as its cost (air storage tank, TES storage tanks and HTF) is a substantial part of the total investment.

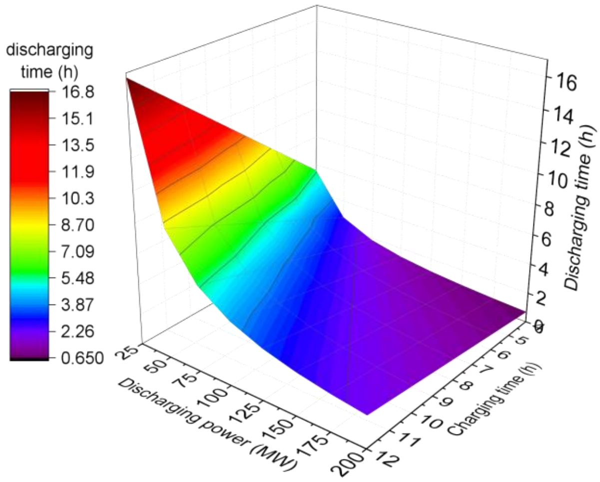


Figure 11. Sensibility analysis for different storage discharging time in function of charging time and discharging power level.

4. Conclusions

The feasibility study of CCGT and ACAES integration into one hybrid power plant performed in this article confirms viability of the concept. CCGT plant is the core of the system and it can be operated standalone. During low load demand ACAES part of the plant can be driven by GT charging the storage. GT compressor can be successfully used as the first stage of ACAES compressor train and other ACES compressors driven by GT shaft reduce GT electrical power output to zero. Additional benefit is that HRSG part of the plant can be still operated at the minimum load during storage charging process, decreasing the total hybrid plant minimum load level to 20% only. The concept assumes 8-hour charging time which should avoid CCGT two-shift operation. ACAES discharging process is fully independent from CCGT process and provides additional 47.5% of power boost over registered capacity of CCGT plant during peak times which lasts for 2 hours in the investigated case.

To demonstrate the feasibility of the concept, TES system used in ACAES part of the plant is based on commercially available two tank system used in CSP plant technology. This rather inexpensive type of TES solution is utilizing Therminol VP1 as HTF. As each sensible heat system, the heat exchange process causes temperature change of the system. Increased hybrid CCGT-ACAES plant flexibility and extended operational range is occupied by 2% lower plant efficiency across GT load level compared to standalone CCGT plant. In conclusion, we believe that this hybrid power plant concept can be successfully implemented, and even more energy density can be offered by TES systems via Phase Change Materials (PCM) or chemical reactions. Further work should be focused on developing other TES system applications for additional round-trip efficiency improvement of the concept.

Appendix A

Table A1. CCGT power plant model parameters.

Parameter	Value	Unit
GT output power (P_{outAIR})	187.55	MW
ST output power (P_{outAIR})	105.90	MW
Total generated power	293.45	MW
GT efficiency	35.45	%
CCGT efficiency	55.42	%
CO2 emission	359.03	kg/MWh
CO2 emission cost	2.53	Euro/MW
Ambient temperature	15	°C
Ambient pressure	1.013	bar
Air inlet mass flow	502.68	kg/s
Fuel mass flow	10.58	kg/s
GT outlet flue gas mass flow	513.26	kg/s
GT outlet flue gas temperature	579.01	°C

Table A2. ACAES power plant model parameters.

Parameter	Value	Unit
Round-trip efficiency	56.78	%
Storage phase		
Air Storage Temperature	50	°C
Air Storage Pressure	70-100	bar
Air Storage Volume	63900	m^3
TES Volume	12006	m^3
TES Cold Tank temperature	40	°C
TES Hot Tank temperature	300	°C
TES Cold Tank pressure	6	bar
TES Hot Tank pressure	6	bar
Air Storage Specific heat loss	20	kW/kgK
Cold TES specific heat loss	20	kW/kgK
Hot TES specific heat loss	1	kW/kgK
Charging phase – air compression		
Compressor Train power	60	MW
Air mass flow	71.75	kg/s
TES thermal fluid mass flow	91.8	kg/s
IC1 intercooler outlet temp	120	°C
IC2 intercooler outlet temp	120	°C
AC aftercooler outlet temp	50	°C
LP1 compressor pressure	2.89-3.16	bar
LP2 compressor pressure	8.37-10	bar
HP1 compressor pressure	24.2-31.62	bar

HP2 compressor pressure	70-100	bar
Charging time	8	h
Discharging phase – air expansion		
Output Power (P_{outAIR})	135	MW
Air flow rate	240	kg/s
TES thermal fluid mass flow	306	kg/s
LP expander temperature (inlet)	290	°C
HP expander temperature (inlet)	290	°C
LP expander pressure (inlet)	8.25-9.9	bar
HP expander pressure (inlet)	68-98	bar
Discharging time	2	h

Table A3. Therminol VP1 parameters.

Minimum temperature	Maximum temperature	Density	Heat conductivity	Isobaric specific heat	Mol weight
°C	°C	kg/m³	W/mK	kJ/kgK	kg/kmol
0	400	817	0.0965	2.3093	165.97

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